An Assessment of the Structural Performance of Rebar-Corroded Reinforced Concrete Beam Members

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Abstract: This paper aims to determine the effects of local corrosion at three different corrosion areas, the (1) entire area, (2) the constant moment area, and (3) the constant shear area, on the flexural performance of RC beams. To analyze this, an experimental study was carried out to prepare two series of RC beams (200 × 300 × 2800 mm) created with three different degrees of corrosion, inducing local rebar corrosion. Furthermore, two series of experimental tests were conducted under different loading types: monotonic and cyclic loading. It was observed that the strength capacity reduction grew in the RC specimens with induced corrosion in the order of the (1) entire area > (2) the constant moment area > (3) the constant shear area, as the average corrosion rate increased. Our test results further showed that the yield and ultimate strength were kept nearly equivalent to the uncorroded RC specimen, with average corrosion rates of 10% and 15%, respectively. Over these corrosion rates, the yield strength and ultimate strength dropped significantly. Compared to the test results under a monotonic loading condition, the structural capacity under a cyclic loading condition decreased, with a more pronounced tendency for each corrosion case as the corrosion rate increased. Longitudinal cracks developed throughout and adjacent to the corrosion areas as the corrosion rate increased. Thus, we can infer that strength reductions may be strongly influenced by these longitudinal cracks.

Keywords: RC beam specimen; local rebar corrosion; degree of corrosion; corrosion rate; corrosion area; monotonic loading; cyclic loading; structural performance

1. Introduction

The deterioration of concrete structures caused by reinforcement corrosion is being reported in an increasing number of structures [1,2]. Subsequently, the importance of making a precise estimation of the durability and the remaining life of rebar-corroded RC structures and drafting a reasonable maintenance and conservation plan has become an essential task [3,4]. To solve this problem, it is necessary to clearly understand the effect of rebar corrosion on RC structures [5–7], and provide an accurate evaluation of the structural performance degradation of RC structures [8–11].

Typically, corrosion is caused by an incorporation into the concrete mixture [12], the attack of chloride ions penetrating via diffusion from the outside [13–19], the carbonation of the concrete cover [17,18,20], or a combination of these issues [21–29]. As corrosion progresses, the expansive displacement at the interface generated by accumulating rust products causes tensile stress in the hoop direction within the concrete cover [30], leading to radial splitting cracks in the cover concrete [11,16,22,28,31–38].

The cracking and spalling of the concrete cover have a significant impact on the bond strength between the rebar and the surrounding concrete cover [5,39–43]. A few analytical
models have been proposed for estimating the residual bond strength of corroded rebars in concrete structures, based on the prediction of crack growth in the concrete cover [5,40,41,44–48].

As corrosion further progresses, the reduction of the rebar’s cross-sectional area, the yield strength of the corroded rebar, the bond strength, and a loss of the concrete cross-sectional area in the tensile area collectively lead to a gradual decrease in the load-carrying capacity of the corroded reinforced concrete structures [4,49–54]. Experimental studies have previously been carried out on the effect of uniform reinforcement corrosion on the residual load-carrying capacity of corroded concrete beams [3,4,48,54–59]. The mechanical behavior of corroded concrete beams is characterized by a reduction in the bending capacity and a shift in the failure mode [10,60–63]. Consequently, the change in failure mode, such as from rebar tensile yielding failure at the earlier corrosion stage or rebar anchorage failure due to insufficient bond strength, must be considered in predicting the residual flexural capacity of the corroded concrete beams [50,54,64,65].

However, in real structures, not every part of the structure deteriorates even though it is of the same member and under the same condition [15,50,66–69]. Similarly, sections of the members and reinforcing bars corrode unevenly [51,70]. The mechanical performance of reinforced concrete structural members is influenced by the complex interplay between the deteriorated and sound parts of the structural member.

This paper aims to determine the effects of local corrosion at three different corrosion areas on the flexural performance of RC beams. To analyze this, an experimental study was carried out to prepare two series of RC beams (200 × 300 × 2800 mm) created with three different degrees of corrosion, inducing local rebar corrosion. And two series of experimental tests were conducted under different loading types: monotonic and cyclic loading.

2. Experimental Program
2.1. Experimental Parameters

This study examines the effects of rebar corrosion on RC beam specimens in terms of the degradation of the mechanical performance. The local corrosion at different areas of the rebar and the degree of rebar corrosion are the parameters used to analyze these effects. Table 1 presents the test parameters used in this study with variables for the rebar corrosion patterns, corrosion levels, and loading conditions. A total of 20 test specimens were fabricated, consisting of one specimen for each experimental parameter.

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patterns of rebar corrosion</td>
<td>Corrosion of the entire area (A)</td>
</tr>
<tr>
<td></td>
<td>Local corrosion in the constant moment area (C)</td>
</tr>
<tr>
<td></td>
<td>Local corrosion in the constant shear area (S)</td>
</tr>
<tr>
<td>Corrosion level (weight loss)</td>
<td>5%, 10%, 30%</td>
</tr>
<tr>
<td>Loading condition</td>
<td>Monotonic loading, Cyclic loading</td>
</tr>
</tbody>
</table>

Three patterns of local rebar corrosion were adopted in this study for the experimental program. The first is the corrosion of the entire area, which has corroded rebars on the entire span length of the beam specimen. Next is partial corrosion in the constant moment area, which has corroded rebars located in the flexural area. The last is partial corrosion in the constant shear area, which contains corroded rebars on the shear area on both sides of the beam specimen.

The average levels of corrosion for the three tested patterns were 5%, 10%, and 30% of the weight loss ratio. To estimate the effect of local corrosion at the three different corrosion areas on the flexural performance of RC beams, two series of experimental tests were conducted under different loading types, including monotonic and cyclic loading.
The corrosion of rebars can be classified into uniform corrosion and pitting corrosion. In this study, pitting corrosion was not within the scope of our experiments. Instead, local uniform corrosion was focused upon.

2.2. Materials and Specimen Preparation

Table 2 presents the mix design and material properties for the concrete mixtures used in this study. Ordinary Portland cement was used with a water–cement ratio of 56.2%. After 28 days, the concrete exhibits a compressive strength of 21.1 MPa and an elastic modulus of 21.06 GPa.

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>w/c</th>
<th>s/a</th>
<th>Unit Weight (kg/m^3)</th>
<th>Slump (mm)</th>
<th>Air (%)</th>
<th>f_c’ (MPa)</th>
<th>f_t (MPa)</th>
<th>E_c (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>0.56</td>
<td>48.8</td>
<td></td>
<td>174</td>
<td>310</td>
<td>866</td>
<td>926</td>
<td>120</td>
</tr>
</tbody>
</table>

The reinforcements used were SD 295A with D13 rebars in the longitudinal at the bottom and at the top, and D10 rebars as the stirrups of the beam. The reinforcement properties are presented in Table 3. The yield strength, the maximum tensile strength, and the elastic modulus of D13 rebar are 412.8 MPa, 589.4 MPa, and 180.9 GPa, respectively. D10 rebars have a yield strength, maximum tensile strength, and elastic modulus of 371.1 MPa, 545.3 MPa, and 216.3 GPa, respectively.

<table>
<thead>
<tr>
<th>Type of Reinforcement</th>
<th>f_y (MPa)</th>
<th>f_u (MPa)</th>
<th>E_s (GPa)</th>
<th>Strain at the Yield Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>D13</td>
<td>412.8</td>
<td>589.4</td>
<td>180.9</td>
<td>177,560</td>
</tr>
<tr>
<td>D10</td>
<td>371.1</td>
<td>545.3</td>
<td>216.3</td>
<td>191,480</td>
</tr>
</tbody>
</table>

A total of 20 test specimens were fabricated, consisting of one specimen for each experimental parameter shown in Table 1, and one reference specimen for each loading condition. Each beam specimen had a 200 × 300 mm square cross-section and was 2800 mm in length. Figure 1 shows the test specimen and reinforcement details. The tension sides of the beam specimens were reinforced with three D13 rebars, and three D10 rebars were embedded on the compression sides.

Figure 1. Test specimen and details of reinforcement.
2.3. Electric Corrosion of Rebar Method

Figure 2 shows a schematic drawing of the test setup used in this study. An acrylic pool containing a sodium chloride (3% NaCl) aqueous solution was fabricated at the surface of the beam specimens by filling it to half of the specimen and inserting copper plates into the pool. This type of corrosion cell, composed of two dissimilar metals (copper and carbon steel) in contact and sharing a common electrolyte (concrete pore solution), is called a galvanic cell [63]. A galvanic current was used to monitor the corrosion process of the reinforcing steel in the present study. As shown in Figure 2, in most studies, galvanic accelerated corrosion is regarded as a method to obtain corroded steel bars quickly, and a 3~5% sodium chloride (NaCl) solution is used [63].

![Figure 2. Electric corrosion method in the case of entire area corrosion.](image)

The location of the pool was adjusted based on the effective area of the concrete surface. An approximately 1 mA/cm² electric current was applied with a power supply between the rebars (an anode) and the copper plates (a cathode).

Figure 3 shows the anode connection methods for local corrosion at the three different corrosion areas ((a) entire area corrosion, (b) constant moment area corrosion: mid area, and (c) constant shear area corrosion: end area) on the flexural performance of the RC beams.

![Figure 3. Anode connection methods.](image)

(a)
Figure 3. Electric corrosion method. (a) Entire area corrosion; (b) Constant moment area; (c) Constant shear area corrosion.

In the case of local corrosion of the entire area, the corrosion area was targeted for the tension side of the main reinforcement and the lower half of the shear reinforcements. To allow the current to flow only through the desired corrosion area, wires were connected to the main reinforcement and shear reinforcement on the tension side. In the case of the constant moment area, the tension side of the main reinforcement and the lower half of the shear reinforcements of the flexural reign were targeted at the 400 mm reign of the mid-span. In the case of the constant shear area, both sides of the shear area were targeted (not the entire shear area, but a 300 mm segment located 20 mm away from the support points).

The corrosion weight loss (%) of the rebar was measured after the tests were completed. The weights before and after corrosion were obtained after eliminating the corrosion products from the corroded sections of the rebar, which were extracted from the concrete using a 10% citric acid and ammonium solution. According to Faraday’s law, the total weight loss of a reinforcing steel bar that is oxidized via the passage of electric charge can be expressed as follows [71]:

$$W_{loss} = [TC] \times \frac{EW}{F} = \left( \sum_{j=1}^{n} \frac{l_j + l_{j-1}}{2} \times (t_j - t_{j-1}) \right) \times \frac{EW}{F}$$

where

- $W_{loss}$ = the total weight loss of the reinforcing steel, g;
- $TC$ = the total electric charge (As, or coulombs);
- $EW$ = the equivalent weight, indicating the mass of metal, in grams, that is oxidized.
For pure elements, the \( EW \) is given using \( EW = \frac{W}{n} \), where \( W \) is the atomic weight of the element and \( n \) is the valence of the element. For carbon steel, the \( EW \) is approximately 28 g. \( F \) is Faraday’s constant in electric charge (\( F = 96,490 \) coulombs, or A\( s \)). \( I_j \) is the current, in amps, at time \( t_j \), in seconds.

2.4. Loading Test of the Specimen Method

(1) Monotonic Loading Test
A static loading experiment was conducted on a corroded reinforced concrete beam specimen. The loading method used in this study was a simply supported configuration, with two-point loads applied at the center of the beam. The shear span-to-depth ratio was 3.33. During the test, both the applied load and the deflection at the center of the span were measured, and the progression of cracks was observed. An overview of the monotonic loading experiment is illustrated in Figure 4.

![Figure 4. Loading method and LVDT installation.](image)

(2) Cyclic Loading Test
In the cyclic loading experiment, the load was set according to the deformation angle of the test specimen, corresponding to different levels: 1/1000 (1.2 mm deflection at the center of the beam), 2/1000 (2.4 mm), 4/1000 (4.8 mm), 8/1000 (9.6 mm), 16/1000 (19.2 mm), 32/1000 (38.4 mm), and 64/1000 (76.8 mm). Each deformation level was repeated three times with load-unload cycles from zero to the respective deformation angle, and then back to zero.

During the loading phase, the displacement was controlled, and loading was applied at the loading point at a speed of 0.025 mm/c. The unloading phase was carried out instantaneously. Figure 5 shows photos of the flexural loading test on the specimen.

![Figure 5. Photos of the flexural loading test on the specimen.](image)
3. Test Results and Discussion

In this study, the test results are presented in terms of the rebar corrosion rate in the concrete beams, the yield load, and the maximum load under different loading conditions and deflection measurements at each loading level. Table 4 summarizes the corrosion weight loss and mechanical test results.

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Pattern of Corrosion</th>
<th>Specimen Name</th>
<th>Corrosion Weight Loss (wt%)</th>
<th>Yield Load (tons)</th>
<th>Max. Load (tons)</th>
<th>Deflection at Yield Load (mm)</th>
<th>Deflection at Maximum Load (mm)</th>
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<tr>
<td>Monotonic Loading</td>
<td>reference</td>
<td>REF-1</td>
<td>0.00</td>
<td>9.30</td>
<td>11.86</td>
<td>10.43</td>
<td>39.03</td>
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<tr>
<td></td>
<td>entire area</td>
<td>A-1-1</td>
<td>9.33</td>
<td>7.65</td>
<td>10.40</td>
<td>8.70</td>
<td>50.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-2-1</td>
<td>13.09</td>
<td>7.95</td>
<td>9.95</td>
<td>6.60</td>
<td>45.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-3-1</td>
<td>-</td>
<td>5.57</td>
<td>7.69</td>
<td>4.46</td>
<td>25.66</td>
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<td></td>
<td>constant moment area</td>
<td>B-1-1</td>
<td>10.76</td>
<td>7.85</td>
<td>11.50</td>
<td>9.40</td>
<td>36.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B-2-1</td>
<td>11.99</td>
<td>8.10</td>
<td>11.15</td>
<td>9.98</td>
<td>34.40</td>
</tr>
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<td></td>
<td></td>
<td>B-3-1</td>
<td>-</td>
<td>7.04</td>
<td>9.77</td>
<td>7.10</td>
<td>45.54</td>
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<tr>
<td></td>
<td>constant shear area</td>
<td>S-1-1</td>
<td>6.63</td>
<td>9.85</td>
<td>11.90</td>
<td>15.96</td>
<td>40.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-2-1</td>
<td>15.81</td>
<td>9.25</td>
<td>11.20</td>
<td>14.81</td>
<td>43.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-3-1</td>
<td>17.98</td>
<td>7.81</td>
<td>10.68</td>
<td>9.29</td>
<td>43.84</td>
</tr>
<tr>
<td>Cyclic Loading</td>
<td>reference</td>
<td>REF-2</td>
<td>0.00</td>
<td>9.20</td>
<td>11.75</td>
<td>12.01</td>
<td>38.40</td>
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<tr>
<td></td>
<td>entire area</td>
<td>A-1-2</td>
<td>10.17</td>
<td>7.95</td>
<td>11.15</td>
<td>8.15</td>
<td>27.91</td>
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<tr>
<td></td>
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<td>A-2-2</td>
<td>10.98</td>
<td>7.75</td>
<td>11.00</td>
<td>7.67</td>
<td>34.78</td>
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<td>A-3-2</td>
<td>33.13</td>
<td>2.80</td>
<td>4.60</td>
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<td></td>
<td>constant moment area</td>
<td>B-1-2</td>
<td>10.47</td>
<td>8.50</td>
<td>11.75</td>
<td>8.92</td>
<td>37.13</td>
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<tr>
<td></td>
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<td>B-2-2</td>
<td>14.17</td>
<td>7.55</td>
<td>10.80</td>
<td>8.47</td>
<td>36.23</td>
</tr>
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<td></td>
<td></td>
<td>B-3-2</td>
<td>21.49</td>
<td>6.00</td>
<td>8.70</td>
<td>6.07</td>
<td>24.73</td>
</tr>
<tr>
<td></td>
<td>constant shear area</td>
<td>S-1-2</td>
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<td>8.45</td>
<td>11.70</td>
<td>8.92</td>
<td>37.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-2-2</td>
<td>14.75</td>
<td>9.35</td>
<td>11.15</td>
<td>14.41</td>
<td>44.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-3-2</td>
<td>12.06</td>
<td>7.48</td>
<td>11.17</td>
<td>7.91</td>
<td>39.86</td>
</tr>
</tbody>
</table>

3.1. Test Results under Monotonic Loading

The evaluation test results of the structural capacity of the RC beam specimens under monotonic loading, according to the corrosion rate of the rebar, are shown in Figure 6. Overall, as the corrosion rate of the rebar increased, the structural capacity of the beam specimens tended to decrease. The deflection values at the yield and maximum load do not provide any meaningful significance.
Figure 6. Deflection of beam versus applied monotonic load. (a) corrosion in entire area; (b) partial corrosion in mid area; (c) partial corrosion in end area.

Particularly, in the case of the rebar corrosion of the entire area, the structural capacity was significantly impaired due to the corrosion of the rebar. For specimens A-1-1 and A-2-1, it was observed that both the yield load and maximum load were substantially reduced to a range between 14.5–17.7% and 12.3–16.1%, respectively. Furthermore, specimen A-3-1 showed a dramatic reduction of 40.1% in yield load and 35.2% in maximum load.

In the case of localized corrosion in the constant moment area, the reduction in the yield load was reduced to 12.9–24.3%, which is a similar extent to the specimens with the entire area corrosion. And the reduction in the structural capacity at the maximum load, at the same corrosion rate, was less pronounced in the range of 3.0–17.6%.

For localized corrosion in the constant shear area, the reduction in the structural capacity was insignificant compared to the entire area corrosion and the constant moment area corrosion cases. The yield load and maximum load were reduced by 0.5–16.0% and 5.6–9.9%, respectively. However, specimen S-1-1 resulted in an increase of 5.9% in the yield load and 0.3% in the maximum load.

Under a monotonic load, the yield load and maximum load of the RC beam specimens, considering the corrosion of the rebar, are presented in Figure 7. Generally, an increasing corrosion rate resulted in a decrease in the structural capacity. However, it was found that localized corrosion in the constant shear area did not significantly affect the structural capacity up to an average corrosion rate of 15%.
As described in the experimental program, the average target levels of corrosion were 5%, 10%, and 30% of the weight loss ratio. Subsequently, the corrosion weight loss (%) of the rebars was measured after the tests were completed. Figure 8 presents the localized average weight loss rates of the tensile reinforcement and stirrups in the monotonically loaded beam specimens after the tests were completed. Overall, it was observed that an increase in the average corrosion rate of the reinforcements resulted in a significant decrease in the load-carrying capacity of the beam specimens. In the case of the rebar corrosion of the entire area, specimen A-2-1 resulted in a slightly higher average corrosion rate from the longitudinal rebar B, compared to specimen A-1-1. An additional average weight loss of 3.8% led to a 4.3% reduction in maximum load capacity. In the case of localized corrosion in the constant moment area, the average corrosion rates from specimens B-1-1 and B-2-1 were nearly identical, and an average weight loss difference of 1.2% caused a 3.0% reduction in the maximum load capacity. For localized corrosion in the constant shear area, the average corrosion rate increased in the order of S-3-1 > S-2-1 > S-1-1. The stirrups in specimen S-3-1 were significantly more corroded and had the lowest maximum load capacity.
Figure 8. Corrosion weight loss of rebars measured at 100 mm intervals along the longitudinal direction under the monotonic loading condition.

Figure 9 illustrates the crack patterns in the concrete cover and the occurrence of cracks with the corroded rebars due to the imposed monotonic loads on the beam specimens. First, it was observed from the reference specimen (REF-1) that flexural cracks mainly occurred at an average interval of approximately 100 mm from the center of the specimen. The middle strip denotes the bottom face of the specimen while the upper strip and lower strip denote the front face and the rear face of the specimen, respectively. During monotonic loading, the failure mode of the beam specimens with corroded rebars was similar to the reference beam specimens. An increase in the corrosion rate of the rebars led to wider crack widths and influenced the crack occurrence under further loading. However, even in the case of specimen A-3-1, with the highest degree of rebar corrosion, concrete spalling did not occur. It is clear from the bottom face that the longitudinal cracks were noticed throughout and adjacent to the corrosion areas (see specimens A-1-1, A-2-1, and A-3-1 for rebar corrosion of the entire area; B-2-1 and B-3-1 for localized corrosion in the constant shear area; and S-1-1 and S-3-1 for localized corrosion in the constant shear area). Specimen A-3-1 clearly shows that the strength reduction was strongly influenced by two main longitudinal cracks at the bottom side and a scattered longitudinal crack at the front side. No diagonal shear failure occurred in any of the specimens.
3.2. Test Results under Cyclic Load

The structural capacity test results of the RC beam specimens under cyclic loading, according to the corrosion rate of the rebar, are shown in Figure 10. Similar to the test results under a monotonic load, as the corrosion rate of the rebar increased, the structural capacity of the beam specimens tended to decrease.

![Figure 10. Test Results under Cyclic Load](image)
Figure 10. Deflection of beam versus applied cyclic load. (a) corrosion in entire area; (b) partial corrosion in mid area; (c) partial corrosion in end area.

In the case of the entire corrosion area, in specimens A-1-2 and A-2-2, Table 4 shows that the average weight loss was nearly identical—about 10.6%—while the yield load and maximum load were reduced to 14.7% and 5.7%, respectively. In specimen A-3-2, it was observed that the yield load and ultimate load reduction were significant, at 69.6% and 60.9%, respectively, with an average corrosion rate of 33.1%.

For localized corrosion in the constant moment area, as the average weight loss increased from 10.5% (specimen B-1-2), 14.2% (specimen B-2-2), and 21.5% (specimen B-3-2), the reduction in the yield load and ultimate load was 7.6%, 17.9%, and 34.8%, and 0.0%, 8.1%, and 26.0%, respectively, as tabulated in Table 4. Over the average of a 20% weight loss, specimen B-3-2 exhibited a considerable deterioration in structural performance.

For localized corrosion in the constant shear area, the reduction in the structural capacity was not as significant as with the other cases.

Under a cyclic load, the yield load and maximum load of the RC beam specimens, considering the corrosion of the rebar, are presented in Figure 11. Compared to the test results under a monotonic loading condition, as shown in Figure 8, the structural capacity in terms of the yield strength and ultimate strength decreased with a more pronounced tendency for each corrosion case as the corrosion rate increased. Excluding the deviated data in Figure 11 (9.35 tons at an average of 14.75% corrosion weight loss, denoted as the solid rectangular symbol), the reduction in the load-carrying capacity due to the average corrosion rates of up to 10% shows a similar trend. However, beyond this corrosion rate, a significant deterioration in the load-carrying capacity was observed especially in the entire area and localized moment area. Over a certain threshold of corrosion, the capacity definitely drops, and cyclic loading worsens this condition. The relationship between the bond strength (shear stiffness) and the level of corrosion of the reinforcements was
suggested in a previous paper [41]. The bond strength decreased considerably due to the slippage between the rebar and the concrete under the tensile region, over a certain threshold of corrosion. This may cause premature failures in the case of cyclic loading [72].

**Figure 11.** Corrosion weight loss (%) versus yield and ultimate loads under cyclic loading condition.

Figure 12 presents the localized average weight loss rates of the tensile reinforcement and stirrups in the cyclic loading conditions after corrosion. Similar to the monotonic load cases, it was observed that an increase in the average corrosion rate of the reinforcements resulted in a significant decrease in the load-carrying capacity of the beam specimens.
Figure 12. Corrosion weight loss of rebars measured at 100 mm intervals along the longitudinal direction under the cyclic loading condition.

In the case of the rebar corrosion of the entire area, similar corrosion loss results were obtained from specimens A-1-2 and A-2-2. At a corrosion rate of approximately 10.6% in those specimens, the average ultimate strength was decreased to 5.7%. It is clearly shown from the test values of specimen A-3-2 in Figure 12 that the average corrosion rate fluctuates based on the location. In addition, about 33% of the average corrosion rate caused a 69.6% drop in the yield strength and a 60.9% drop in the ultimate strength. In the case of localized corrosion in the constant moment area, a gradual increase in the average corrosion rate in the order of B-3-2 > B-2-2 > B-1-2 led to corresponding strength reductions. For localized corrosion in the constant shear area, the average corrosion rate increased in the order of S-2-2 > S-3-2 > S-1-2. Although specimen S-1-2 was corroded at a rate of 7.9%, the ultimate strength was equivalent to the reference specimen. However, specimens S-2-2 and S-3-2 corroded at rates of 14.8% and 12.0%, causing an ultimate strength reduction of 5.1% and 4.9%, respectively.

Figure 13 illustrates the crack patterns in the concrete cover and the occurrence of cracks with corroded rebars due to the imposed cyclic loads on the beam specimens.
Except for specimen A-3-2, approximately 100 mm crack intervals were observed from the center of all specimens.

![Figure 13. Distribution of cracks for each specimen under cyclic load.](image)

Similar to the monotonic loading case (see Figure 9), the bottom face clearly shows longitudinal cracks throughout and adjacent to the corrosion areas (see specimens A-1-2, A-2-2, and A-3-2 for rebar corrosion of the entire area; B-3-2 for localized corrosion in the constant shear area; and S-2-2 and S-3-2 for localized corrosion in the constant shear area). Furthermore, specimens A-3-2 and B-3-2 clearly show that the strength reductions were strongly influenced by a couple of main longitudinal cracks at the bottom side. Specimen A-3-2 particularly exhibits two main flexural cracks toward the two load points, which might be attributed to the occurrence of very high local corrosion, along with the longitudinal rebars B and C aligning with the load points. No diagonal shear failure occurred in any of the specimens.

4. Conclusions

This paper aimed to determine the effect of different corrosion rates on the flexural performance of RC beams. To analyze this, an experimental study was carried out by preparing two series of RC beams and inducing local rebar corrosion at three different corrosion areas: (1) the entire area, (2) the constant moment area, and (3) the constant shear area. Two series of experimental tests were conducted under different loading types using monotonic and cyclic loading. The results acquired from this study are described below:

1. The yield load and ultimate load of the RC beams decreased with the increase in the rebar corrosion rate, regardless of the imposed corrosion areas and the loading types. This was consistent with the observed surface longitudinal cracks that developed throughout and adjacent to the corrosion areas as the rebar corrosion rate increased.
(2) It was observed that reductions in the ultimate load and yield load became larger in the order of the corroded RC specimens induced at (1) the entire area > (2) the constant moment area > (3) the constant shear area, compared to the value of the referenced uncorroded RC specimen, as the average corrosion rate increased.

(3) The test results further revealed that the yield strength and ultimate strength were kept almost equivalent to the uncorroded RC specimen, with average corrosion rates of 10% and 15%, respectively. Over these corrosion rates, the yield strength and ultimate strength were evidently dropped.

(4) Compared to the test results under the monotonic loading condition, the structural capacity under the cyclic loading condition decreased with a more pronounced tendency for each corrosion case as the corrosion rate increased. Over a certain threshold of corrosion, the capacity definitely drops, and cyclic loading worsens this condition, presumably due to the bond slippage.

(5) The crack spacings in the flexural zone were nearly identical, irrespective of the different corroded RC beams and loading types. A longitudinal crack was developed throughout and adjacent to the corrosion areas, as the corrosion rate increased. It is thus inferred that strength reductions may be strongly influenced by the occurrence of longitudinal cracks.

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